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(54) Sensor system

(57) A sensor system comprises a dual mode optical fibre 116 with sensitive areas 34 into which FMCW light is launched by laser 31. The input light is reduced to a single first mode by device 114. Deformation of the fibre 116 will result in light partially switching from the first mode to the second mode, which will then propagate along the fibre at a different velocity and thus reach detector 19 at a different frequency from light in the first mode. Beating (heterodyning) will result whose frequency gives the position of the deformation.

As shown in Fig. 3, the two modes are transversal modes, but they may alternatively be polarization modes (Fig. 1A, not shown). Deformation may result from the fibre being trodden on by an intruder, or by pressure by a heat-sensitive member in a fire alarm.

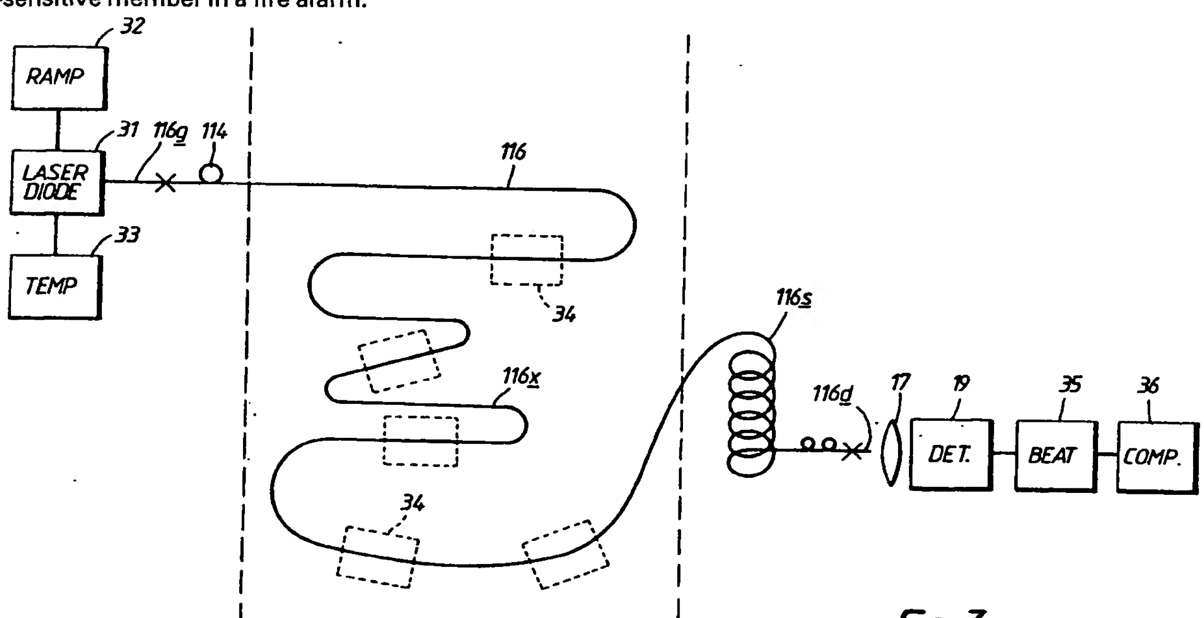

FIG. 3.

The drawings originally filed were informal and the print here reproduced is taken from a later filed formal copy.

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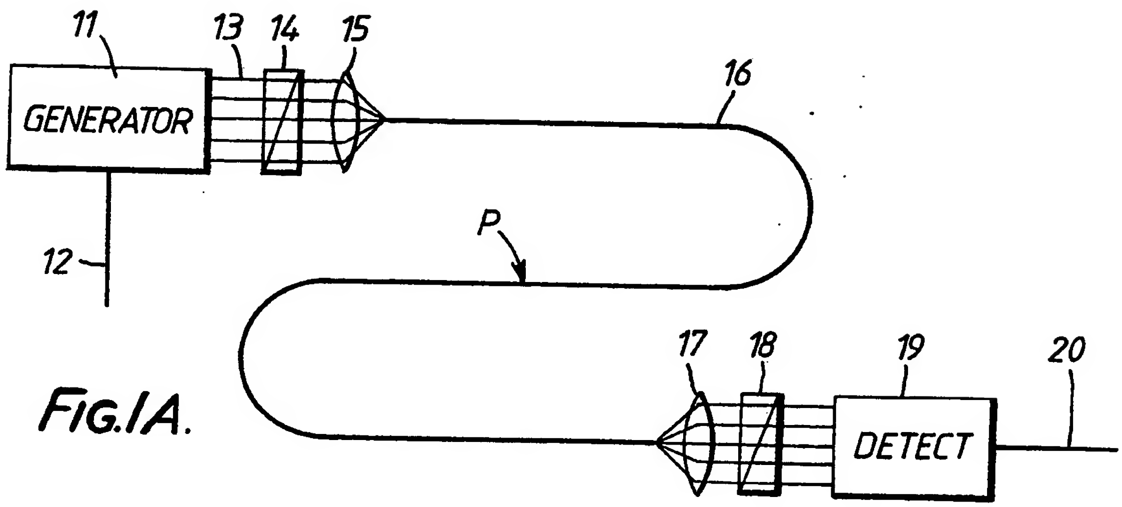

FIG. 1A.

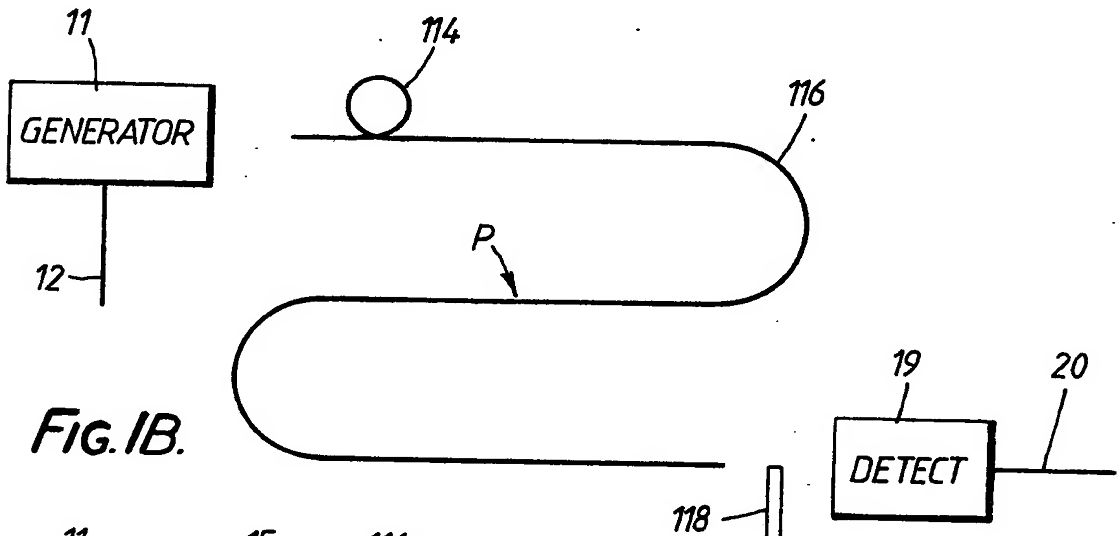

FIG. 1B.

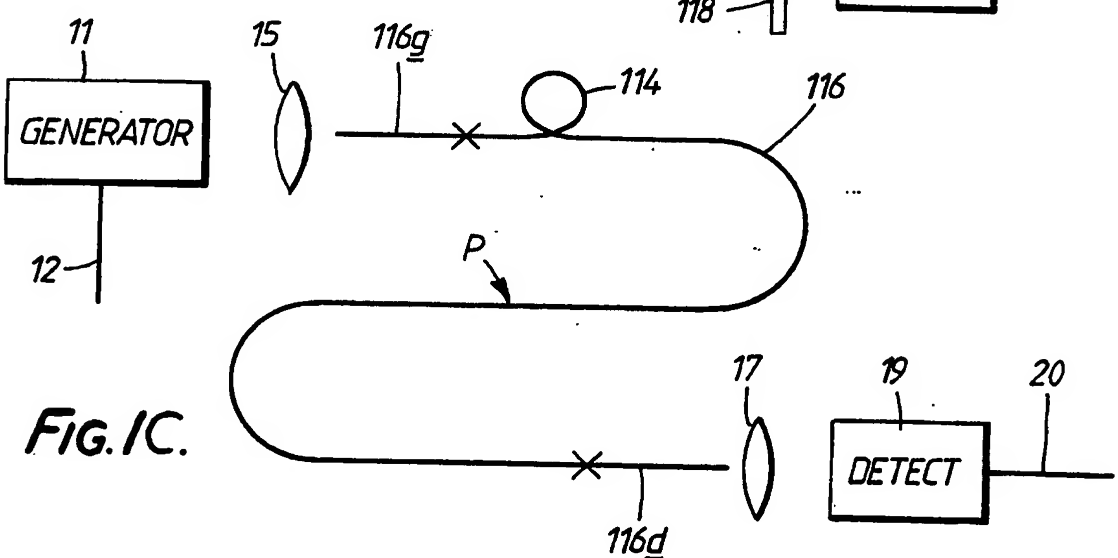

FIG. 1C.

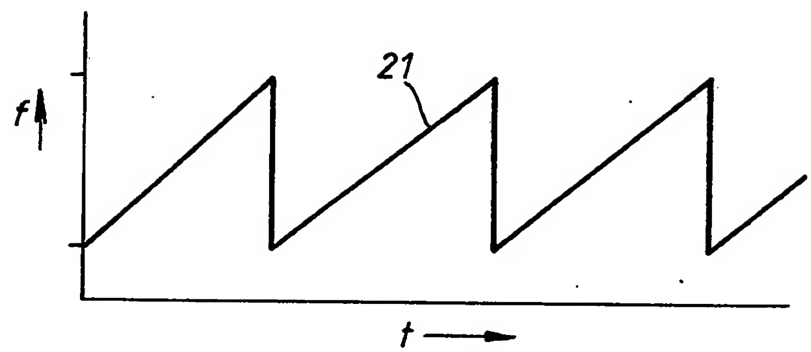

FIG. 2A.

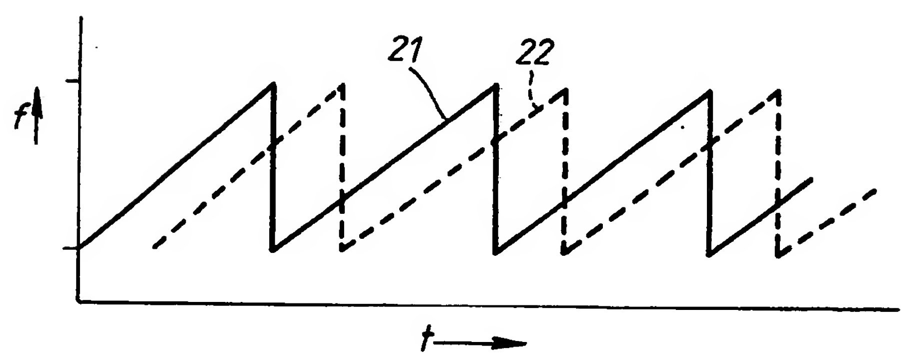

FIG. 2B.

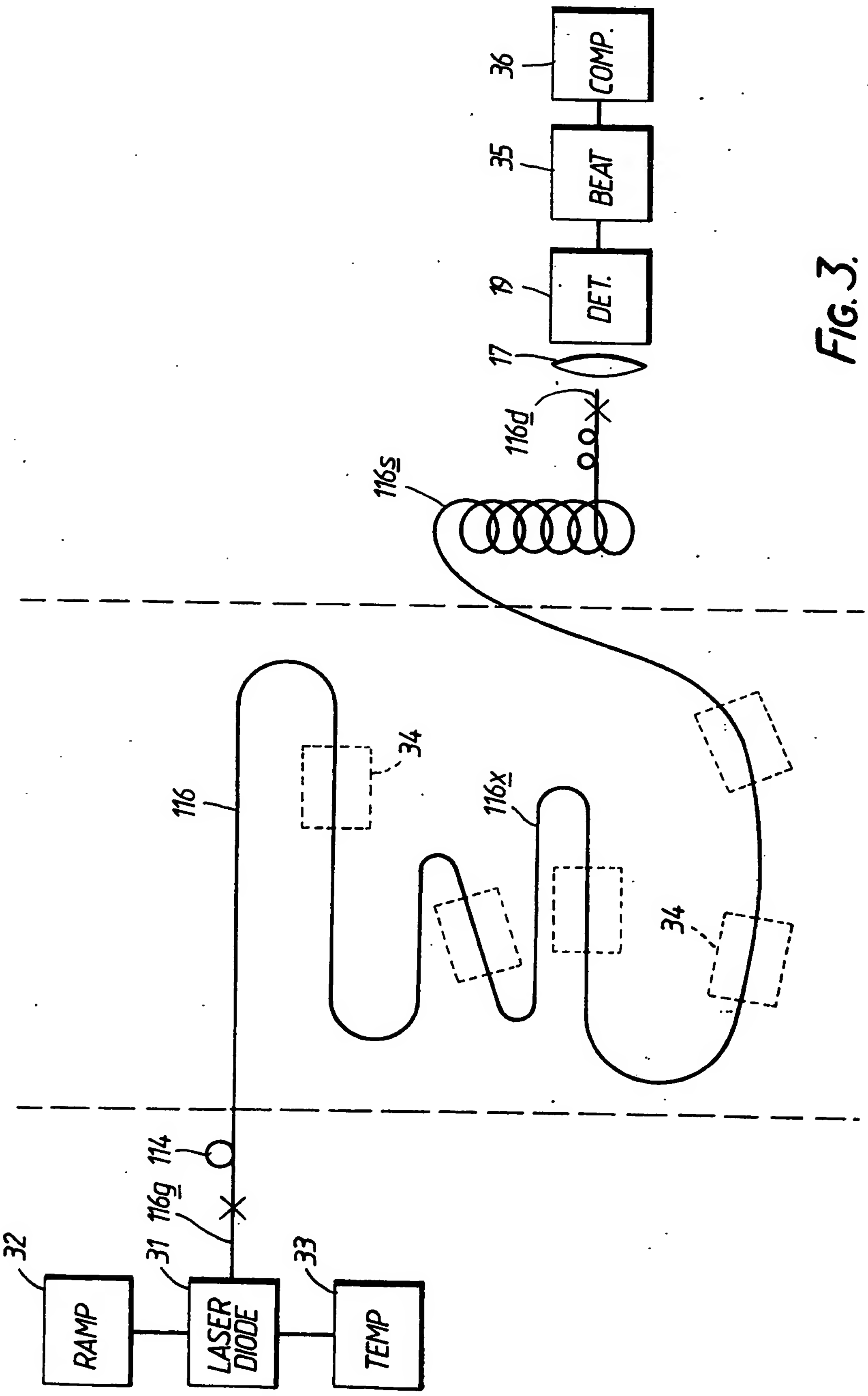
36
COMP.
35
BEAT
19
DET.
17
116d
116s
116
34
116x
34
114
116g
31
32
RAMP
LASER DIODE
33
TEMP

FIG. 3.

SPECIFICATION
Sensor systems

This invention concerns sensor systems, and relates in particular to such systems that employ a distributed, or extensive, sensor device.

It is well known to employ sensor systems to provide information about a certain aspect of the ambient conditions at a locality. Such systems generally comprise one or more signal-providing sensor/detector device operatively connected to apparatus for acting upon the output signal. Moreover, it is commonplace for the actual sensor device to be *remote* from the remainder of the sensor system, aand to output a signal (representing the relevant ambient state) that is then transmitted — typically in electrical form along conductive wires — to the remainder of the system to initiate whatever action or response is required. One example of such a system is the combined burglar/fire alarm equipment now found in many premises, both industrial and domestic. In this sort of system a central monitoring station is connected by numerous wires to a multiplicity of sensor/detector devices — thermocouples for detecting heat, light sources/photocells for detecting smoke or the presence of an opaque body, pressure pads for detecting the presence of a weighty body, ultrasound transmitters/receivers for detecting movement, and so on. Each device transmits to the central monitor information about what, if anything, it has detected, and the monitor is "programmed" to initiate the appropriate action — which might be to turn on the sprinklers and call the fire brigade, or lock all the doors and call the police.

One of the problems associated with systems of this general type — a multiplicity of sensor devices wired up to a monitor — is that of necessity each sensor device has needed to be connected to the monitor in a manner such that the monitor may know which sensor is sending it what information (it is, after all, rather excessive to operate the entire sprinkler system in a 15 storey office building when the culprit is a wastepaper basket in room 502!). This has in the past meant either a complicated multiplexing arrangement, or a great deal of wiring, which makes the system expensive to install and difficult to repair should the wiring become faulty. Moreover, it is not unusual for electrical wiring to generate sparks, so this type of system is not easy to use in circumstances where the presence of flammable or explosive materials dictates that sparks cannot be tolerated. The present invention seeks to overcome these problems, amongst others, by providing a novel sensor system in which there is employed a somewhat unusual type of sensor device, namely one that is (a) non-electrical, and (b) distributed — that is, that extends in space — and yet will output to a monitor a signal that can, with a sufficient degree of precision, locate the origin within its extent of any particular output to the monitoring part of the system. More specifically, the invention proposes the use of a particular type of optical fibre — a linearly extensive object that may be many metres (even kilometres) long — as a sensor device when used in conjunction with appropriate means both for launching light wave energy thereinto and for receiving such energy after its passage along the fibre..

Optical fibres are waveguides for electromagnetic radiation at the wavelenghts/frequencies of light. Like any other type of waveguide they can support — that is, carry — wave energy in several different modes. It is not necessary, here, to explain in detail the concept of waveguide modes, but it is to be noted that in optical fibres these modes can be polarization modes or transversal modes, and that it will generally be the case that light energy of one mode passes along the fibre at a speed different from light energy of any other mode (though this is not always so, and if two distinct modes travel at the same velocity then for the purpose of this invention and the following discussion, they are treated and referred to as the same mode (i.e. a set of modes); an example of this is so-called single-mode fibre, which in reality guides two modes — the two orthogonal polarization modes — which travel at approximately the same velocity down the fibre). It is also useful to observe that, unlike a conventional conductor, there is a definite connection between a waveguide's physical dimensions (transverse to the guide axis) and the wavelength of the energy that can propagate without significant loss along the guide, and except for the fundamental mode all the modes of an optical fibres have a "cut-off" wavelength (for wavelengths longer than that particular wavelength that mode will not propagate down the fibre); the fundamental mode does not possess a cut-off, and is always guided. For an optical fibre to be single mode (i.e. only the fundamental mode is left), the core of the fibre must be small (4 to 10 microns diameter) and the difference in index between the core and cladding must be small (about 0.004, typically). The fibre itself can be any size that is significantly larger than this (typically 60 to 150 microns), but the light itself is only guided down the small central core of the fibre. By making the wavelength a little shorter a second set of transversal modes will begin to propagate down the fibre (this set is referred to as the second mode of the fibre, since all the modes in the set propagate at approximately the same velocity). In such a case — in this wavelength range — the fibre may be referred to as two-transversal mode fibre. Fibre exists in which the two polarization modes propagate with significantly different velocities. This fibre is usually called "birefringent" fibre or "polarization-preserving" fibre. As is discussed further herinafter the invention to be described can use either birefringent fibre or two-transversal mode fibre in its operation, and the phrase "two-mode fibre" is used to describe either of these two kinds of fibre since they both guide two (sets of) modes at different velocities.

It is known that lightwave energy of one mode travelling down an optical fibre capable of supporting two different modes can be caused to transfer, at least in part, into the other mode if the fibre is made to undergo some physical, dimensional, perturbation. For example, if light

energy linearly-polarized (e.g. vertical) is passed along a fibre capable of maintaining polarization, and that fibre is then appropriately dimensionally perturbed (by, say, squeezing it) then some of the energy will transfer into the mode in which it is linearly-polarized at right angles to the original polarization (e.g. horizontal). Alternatively, if light energy in a fundamental mode is passed along a fibre capable of supporting two-transveral modes, and that fibre is then dimensionally perturbed (again, say by squeezing it), then again some of the energy will transfer into the second order mode state. The invention proposes that this effect — the transfer of energy from one mode to another by the dimensional perturbation of an optical fibre capable of supporting both modes — be used in the construction of a sensor system in which the optical fibre constitutes an extended, distributed, sensor device. Clearly, a single optical fibre of many metres length can be operatively linked to a multiplicity of perturbation-inducing devices (sensitive to such things as temperature, sound, movement and pressure) distributed therealong so as to give some form of output (light energy in a mode other than that in which the energy was originally fed into the fibre). The problem, however, is to identify where, along the fibre's length, the perturbation occurred — a problem which is solved, in the invention, by employing light energy having a time-varying frequency, and then comparing the frequencies of the two different-mode outputs (which travel at different speeds, so one is a delayed version of the other) to determine the delay, and thus — knowing the speeds — by calculation the distance back along the fibre to the perturbation point.

In one aspect, therefore, the invention provides a distributed-sensor system comprising:

a) an elongate sensor element, in the form of an optical fibre capable of supporting two modes of lightwave energy travelling along the fibre from one end to the other and, upon undergoing some localised physical perturbation, of allowing some of the energy in one mode to transfer at the perturbation locality to the other mode;

b) variable frequency continuous wave lightwave generation means, for generating lightwave energy to be launched into the fibre at one end thereof, the frequency of the lightwave varying with time;

c) single mode lightwave launch means at one end of the fibre, for launching the generated energy into the fibre in one of the two modes the fibre can support;

d) perturbation-inducing means at a locality somewhere along the fibre, for inducing a physical perturbation, or dimensional change, in the fibre, and thus for causing some lightwave energy to transfer across at that locality to the other of the two modes the fibre can support;

e) mode mixing and receiving means at the other end of the fibre, for mixing whatever lightwave energy arrives in the two modes at that end of the fibre, aand for providing an output related thereto that varies in some manner dependent on the difference in frequency of the two lightwaves; and

f) position computing means operatively linked to the double mode lightwave receiving means, for calculating from the latter's output the position along the fibre of the induced perturbation.

The sensor system of the invention is one having a distributed sensor — that is, a sensor (an actual sensing element) that extends over a relatively large length. Specifically, the sensor system includes an elongate sensor element in the form of an optical fibre; this fibre may be of any length, from a few metres up to several hundred metres — or even a few kilometres (the actual length will, of course, be whatever best suits the particular application of the system, though it should be borne in mind that the lightwave generating means will need to be powerful enough to launch into the fibre sufficient energy to reach the far end).

The fibre will in general be divided — notionally — into three portions. The midle portion is the "active" part of the fibre, where it is truly a sensor element capable of responding to perturbing forces (discussed further hereinafter). At either end, though, there will be a (usually "inactive") portion of fibre; these merely couple the active portion to the launch means (at the "in" end) and the receiving means (at the "out" end). However, it is desirable if the length of fibre supporting the two modes and beiong the sensor element portion be coupled to the receiving means (at the "out" end) by a similar length of two-mode fibre. As explained in more detail hereinafter, this renders easier the problem of computing from the receiving means output where, along the active sensor length, the perturbation occurred.

The system of the invention may, of course, include more than one elongate sensor element. It might, for example, be desirable to have a back-up element paralleling a main element, to have separate elements for each different type of sensory input, or to have different elements extending in different directions from some central monitoring station.

The inventive sensor system uses a sensor element in the form of an optical fibre capable of supporting two modes of lightwave energy and allowing energy transfer from one mode to the other. One very convenient pair of modes is the two modes represented by two orthogonal linear polarized lightwaves. It is now technically possible to manufacture birefringent fibre — that is, fibre capable of supporting either of the two linearly-polarized modes with no significant coupling between them (until the fibre is subjected at some point to a physical perturbation, causing a localised deformation, whereupon lightwave energy transfers across to the other mode, and from there on the fibre is carrying light in both of the two polarizations). Another convenient pair of modes is the two supported by a two-transversal mode guide. Such a guide is, as mentioned hereinbefore, one wherein the transverse dimension is just a little too large for the wavelength with which it used — that is, it is single mode for any wavelength longer than a predetermined "cut-off" wavelength, but is in fact used with a wavelength just a little shorter than the cut-off value. As explained further below, the

generation of the lightwave energy, and its launching into the fibre in only one of the chosen two possible modes, depends on the type of mode pair — on whether they are polarisation modes or transverse modes.

It is not impossible to envisage a system wherein the fibre is capable of supporting more than two modes of lightwave energy, and allowing energy in one mode to be transferred across to one or more of the other modes, the lightwave mode mixing and receiving means then being able to detect the mixed energy arriving in any combination of the modes. At this time, however, the detection of the mixed energy and the resolution of the result into some semblance of sense, is technically very difficult. Thus, there seems no need to have more than two modes, or to have a fibre specifically capable of supporting any extra.

The optical fibre employed as the elongate sensor element supports lightwave energy in two modes — the types of mode pairs discussed mainly herein are the two linear polarization modes and the two transversal modes, but other pairs (circularly-polarized/linearly polarized, for example) are not excluded, provided the two have sufficiently different propagation velocities in the chosen fibre. Other than determined by the requirements of mode support, however, the lightwave energy can be of any optical wavelength (including Infra-Red and Ultra-Violet); the fibre will naturally be selected accordingly. Suppliers of suitable fibres demonstrating a high velocity mismatch between modes are York Technology Ltd, Andrew Corporation (USA), ITT (USA) and Corning (USA). Two fibres from York Technology Ltd are H B 800/2 (a polarization maintaining fibre), for light of about 830nm wavelength, giving a beat length of around 2mm and an attenuation of less than 5dB/Km, and SM800 (a special sample of this was surprisingly a double-mode fibre at 830nm; its attenuation at 1300nm is around 2dB).

The fibre will be of a type selected to suit the modes it is to support — of birefringent material for polarization modes, or any single mode fibre with the appropriate wavelength range for transversal modes. However, only that portion of the fibre that is to act as the sensor element itself — the "active" portion — need be of the special form.

The fibre employed in the inventive system supports two modes of lightwave energy, and upon undergoing some localised physical perturbation allows some energy travelling along it in one mode to couple — to be transferred — across to the other mode. It is, in fact, a well-known property of waveguides generally that (abrupt) dimensional changes in the guide will cause energy to couple from one mode the guide can support to another (the mechanism by which this happens need not be explained here) and this is certainly so in optical fibre guides. In an optical fibre the relevant physical change is a change in the refractive index of the fibre; while it may not be easy to appreciate, this change can be caused simply by mechanically squeezing the fibre, thus reducing its transverse dimension (of both core and cladding) correspondingly. The way in which the dimension-change-engendering physical perturbation is effected is discussed further hereinafter.

The perturbation of the fibre results in some of the lightwave energy travelling along the fibre in one mode transferring to the other mode; how much energy transfer depends, amongst other factors, on the degree of the perturbation (the more the fibre is squeezed, the more energy transfers) and the spacial distribution of the perturbation (a sequence of perturbations spaced apart by a wavelength-dependent amount can transfer more energy than a single perturbation). While it is possible to transfer almost all of the energy, this would be pointless (there would be no subsequent mixing), and transferring small amounts — of the order of 10% or less — is preferred both to leave some for subsequent transferral further down the fibre and to avoid the problem of cross coupling.

As stated hereinbefore, it will be the case that the speed of propagation of lightwave energy travelling along the fibres is different in each of the two modes — thus, that energy in one mode travels slower than energy in the other mode. It is this difference in speed (which results in a delay in the arrival of lightwave energy in one mode as compared with that in the other), coupled with the use of a continuous wave lightwave generation means that generates lightwave energy with a time-varying frequency, that is at the heart of the present invention, as is explained further hereinafter. A typical propagation speed difference would be of the order of 1/1000 of the speed of light in the fibre, or 0.1%, which, for a fibre of about 1 Km length, with the light travelling at roughly 2×10^{10}cms/sec, could give rise to a delay of up to 5 nanoseconds.

In the sensor system of the invention continuous wave lightwave energy is launched into and passed along an optical fibre. The means for generating this lightwave energy prior to launching it into the fibre is a variable frequency means, by which is meant that the generating means can output continuous wave lightwave energy of some selected frequency (and thus wavelength) that is variable (at will) over a range of frequencies (and thus wavelengths). A typical example of such a generating means is a single mode laser diode of the MITSUBISHI ML2701 or HITACHI HLP1400 type. The output of this latter laser is continuous wave lightwave energy at about 830nm (this is dependent on the driving current).

The lightwave energy generation means provides lightwave energy the frequency (and thus wavelength) of which varies with time. The purpose of this variation — as is explained in more detail hereinafter — is to allow the relatively simple determination of what is in effect the delay between the arrival at the receiving means of energy travelling along the fibre in one of the two modes and energy travelling in the other (at the receiving means the frequency of the energy in the slower mode will necessarily lag behind that in the faster mode, and the two can be combined to generate beats the frequency of which is a measure of the delay). For this determination to take a simple form it is desirable that the time variation of the

frequency of the generation means' output be equally simple and regular, and ideally the change would be a constant rate linear increase or decrease in frequency. Over any substantial length of time this is impractical, however, and as a compromise it is preferred to saw-tooth ramp the frequency at a "constant" rate over some useful range (appropriate to the generation and receiving means) — thus, to increment (or decrement) the frequency from one value to another, then "instantly" return it to the first value and again increment/decrement it to the second, and so on. The actual rate at which the frequency of the generating means output is varied, and the time for a complete scan over the available range, is not important, save that — as will normally be the case — the rate should be low, and the range scan time long relative to the expected delay in the arrival (at the receiving means) of energy travelling in one mode as compared with that in the other. A typical range scan (ramp) time would be about 1 millisecond (1×10^{-3} seconds), which is long compared with a possible delay time generally of the order of tens of nanoseconds (5 nanoseconds in the example given hereinabove).

The output of the variable frequency continuous wave generating means is lightwave energy that is to be launched into the fibre in one of the two modes the fibre can support. This requires launch means, and while in certain embodiments the launch means includes positive means to ensure that the energy is launched in the required one mode only, in others it may be necessary merely to "shine" the lightwave energy into the fibre, possibly *via* a lens. For example, if the generation means provides a non-polarized output, then its output needs be passed to the fibre *via* a suitably orientated linear polarizer (a Nicol prism, say), whereas if the output is itself linearly polarized (as may well be the case with some laser diodes) then it is necessary merely correctly to align the fibre and then direct the output into the fibre (in such a case the fibre can be pigtailed onto the diode directly). Again, if the lightwave energy is to travel down the fibre in one of the transversal modes then it should be fed into the fibre *via* a mode filter to remove the unwanted (higher order) mode — typically a relatively tight coil of fibre around which the unwanted mode cannot travel. Thus, the launch means allows the generation means' output to be fed into the fibre in the correct mode, and as appropriate it may include a mode filter of some sort for enabling this to be done.

While in principle it may not matter in which mode the lightwave energy is launched, for energy in either mode will transfer to the other when the fibre is physically perturbed, nevertheless in some cases the manner in which the 'wrong' mode energy is to be filtered out (leaving only energy in a single mode travelling down the fibre) does predetermine the mode. In the example given above, for instance, the use, as a mode filter, of a tight loop of fibre to filter out higher order mode energy necessarily means that the energy travels on down the fibre in the lowest order mode.

The sensor system of the invention relies upon lightwave energy being transferred from one of two modes to the other as a result of a localised physical perturbation of the fibre, and requires perturbation-inducing means to cause this to happen. This perturbation-inducing means can be an actual device (that, triggered by some feature of the ambient conditions, physically perturbs the fibre at a chosen location), but it may also be merely the absence of any fibre-distortion protection. An example illustrating the former concept might be a temperature sensitive device wherein a fixed rigid member expands into squeezing contact with the fibre as the temperature rises, while one to explain the latter would be a length of fibre hidden under a carpet, where there is no positive device for perturbing the fibre, but it can nevertheless be perturbed simply by the pressure thereon as someone walks over the carpet where it lies. There will, therefore, always be means whereby a physical perturbation and dimensional change can be induced, but this means may not be an actual device.

There may, of course, be several perturbation means, and these may be of different kinds. Indeed, it is a prime purpose of the invention to enable the construction of a system where a single sensor element — the fibre — extends over a considerable length, so allowing the gathering of data relating to the ambient conditions at many places therealong. In the case of the under-the-carpet embodiment mentioned above, where there is no specific perturbation device, the fibre can be perturbed anywhere along its length — anywhere throughout the rooms, and the building, where it is laid — simply by someone walking about in any of the areas through which the fibre runs. Alternatively, in the case of a multi-detector fire alarm system, with each detector using a thermally-driven expanding member (as mentioned above) to press upon the fibre, the fibre can be perturbed anywhere along its length where a detector has been sited. Naturally, one fibre could have both these uses — within each part of the building it could be both laid under the carpet and run (to the next area, say) *via* a heat detector, or alternatively it could run through all the rooms under the carpet on the outward journey and *via* a series of heat detectors on the return journey. In either case a simple calibration would allow a distinction to be made between the two sorts of inputs (if the calculated distance did not equate to the known position of a heat detector then it must be derived from someone walking around).

Incidentally, it will generally be most convenient to have the fibre in a loop, so that the two ends — and the equipment connected thereto — are physically in the same place.

At the end of the fibre distant from the single mode launch means there is the mode mixing and receiving means, at which the lightwave energy arriving in either of the modes is mixed with the energy (if any) in the other, the combination is "detected", and there is provided an output relating to the difference in frequency between the energies in the two modes. The detector component may be any light-sensitive device — a photocell or

photodiode, say — suitable to the lightwave energy involved, and may therefore be UV- visible- or IR-sensitive as required. Thus, for use with either of the two laser diode generation means mentioned above a suitable receiving means detector component is an R.S. large area photodiode (stock No. 303—647) with a spectral range of 350 to 1150nm. The provision of an output relating to the frequency difference involves a comparison (or combination) of the two signals; for obvious technical reasons this is best achieved by combining — mixing — the two received lightwave energies before detection, allowing them to interfere, and then detecting the result. This matter has already briefly been touched on above, but is now explained in more detail.

Two identical continuous wave signals arriving at the same point and being combined will interfere constructively or destructively — that is, they will add together to produce either a larger or smaller signal — depending on their relative phases at the point. Signals that are exactly in phase — in step — will add to give a larger signal, while signals that are exactly out of phase — two sine waves, for example, one 180° (π radians) out of phase — will "add" together to produce a smaller signal (in the case of two identical sine waves, a zero signal). Out of phase — out of step — signals produce some intermediate addition signal. The actual phase of each signal at the chosen point depends upon the frequency/wavelength of the signal and upon the pathlength from the signal source to the point. If the chosen point is then displaced, so that the pathlength to it for each signal is different, then in-phase signals become out-of-phase (and some out-of-phase signals become in-phase). Moving the point steadily causes the two signals regularly to go in and out of phase giving regular large and small (possibly zero) combinations.

If the two continuous wave signals are of different frequencies (and thus wavelengths) then they will arrive at the chosen point with continuously varying relative phases (in a manner that is time dependent the two will sometimes be in phase but mostly-not). Two frequencies that are only just different will move in and out of phase quite slowly, while two that are considerably differnt will move in and out of phase quite quickly. In any case the additive combination of the two signals will vary from being large to being small, and will do so at a rate that depends upon the relative size of the frequency difference (small difference, small rate, and *vice versa*). This cyclic variation of the amplitude of the combined signals itself forms a third signal; the phenomenon is called "beating" — the two signals beat with each other to cause beats — and the frequency of the beats — the "beat frequency" — is dependent upon, and thus a measure of, the difference in frequency between the two.

In the system of the invention there is employed a continuous wave signal generator that outputs (for launching into the fibre) a signal whose frequency varies (preferably at some constant rate) with time, so that at any two particular times (within the operation cycle for a ramped generator) it has two different frequencies. Launched at time T this signal travels along the fibre in one of two modes, at a first speed; at some position along the fibre, and when it has a frequency f_1, part of the energy transfers across to the other of the two modes, and continues to travel on down the fiobre but at a *different* speed. Accordingly, both signals eventually reach the receiving means, but one is delayed relative to the other because it propagates down the fibre more slowly. All this time the generated signal frequency has been changing; when the fast signal (at frequency f_1) reaches the detector the slow signal (also at f_1) still has some way to go, but when the slow signal finally gets there after an extra time t the frequency of the fast signal has changed to f_2 (which is what was being launched into the fibre at time $T + t$). The difference between the two frequencies, $f_1 - f_2$, is dependent (possibly amongst other factors) on the delay t experienced by the slower signal, and that in turn is dependent upon the distance the slower signal had to travel (for naturally the larger the distance the longer it takes). Thus, the frequency difference is a measure of the distance back along the fibre to the point where some of the signal energy transferred across from one mode to the other — or where the fibre was physically perturbed. Now, since — as explained above — any frequency difference causes beats when the two signals are subsequently combined, and the frequency of these beats is dependent upon the magnitude of that difference, so the distance to the perturbation locality can be deduced from the frequency of the beat.

As mentioned hereinbefore it is preferred if there be, between the length of active sensor element fibre and the receiving means, a similar "active" length which is not used as part of the sensor element — i.e. is not subject to perturbations — and merely couples the active length to the receiving means. From the foregoing explanation the reason for this will now be clear; since the beat frequency varies directly as the delay, and the delay varies directly as the distance, to get any significant delay giving a measurable beat frequency that can be readily distinguished both from noise associated with low frequencies and from sidebands originating in the ramp frequency, there must be a corresponding significant length of sensor element fibre "down stream" of the perturbation locality. This can be ensured by having the extra length of two-mode fibre, not subject to perturbations, adjacent the receiving means.

By combining the lightwave energies arriving in each mode and detecting this combination so there is produced an output that "beats" with a frequency dependant upon the distance along the fibre to the perturbation locality. The actual manner in which the two energies are combined may be any that is convenient and appropriate to the nature of the two modes. For example, when the two modes are orthogonal linear polarization modes, supported in a birefringent fibre, an "analyser" set at 45° to each will pass a proportion of both in the common plane (so that they will now be able to interfere, and thus combine, at the detector to produce the desired "combination" output). Alternatively, where the two

modes are transversal modes, these can be combined merely by partially blocking the "out" end of the fibre before allowing the resultant energy to fall onto the detector (as will be understood, and need not be explained further here, transversal modes have different spatial field patterns, and can be effectively mixed by spatially filtering the two modes together — thus, the partial blocking, by some opaque member, of the light exiting the fibre automatically combines the two energies as they radiate past the partial block). Where the sensor element fibre is spliced to another length of fibre, as mentioned hereinbefore, this splice — provided it is a fairly *bad* splice — will itself act as the blocking member causing the two transversal modes to combine.

The final component required for the invention is means for accepting the output of the receiving means, and computing therefrom the position along the fibre of the perturbation locality. In essence this computing means is little more than a device for outputting a signal — the distance information — the magnitude of which is directly proportional to the beat frequency of the receiving means output, and no more need be said about it here. However, in practice the situation is complicated by the beat frequency being related not only to the perturbation position, as explained above, but also to factors such as the actual lightwave energy frequency, the rate of change of this, and the ramp sawtooth frequency (as used in a preferred embodiment).

Various embodiments of the invention are now described, though only by of illustration, with reference to the accompanying drawings in which:—

Figures 1A, B and C show schematically the principle of three simple sensor systems of the invention;

Figures 2A and B show ramped lightwave energy inputs and outputs relevant to the invention; and

Figures 3A and B show a slightly more realistic, but still schematic, version of Figure 1*C*

The principle of the inventive sensor system is illustrated by Figures 1*A*, *B* and *C* and Figures 2*A* and *B*. The Figures 1 show the mechanical arrangement, while the Figures 2 show the input and output signals.

In Figure 1*A* there is shown the heart of a simple sensor system in accordance with the invention. A lightwave energy generator (11; controlled along line 12) outputs Frequency Modulated Continuous Wave (FMCW) light (13) that is launched, *via* a polarizer (14) and focusing lens (15), into one end of a length of birefringent optical fibre (16). This light passes along the fibre to the other end thereof, where it exits and is received, *via* a collecting lens (17) and an analysing polarizer (18) with its axis at 45° to that of the input polarizer 14, by a detector (19; giving an output on line 20).

The generated lightwave energy is FMCW energy, and its frequency is controlled by signals passed into the generator along line 12 (neither these signals nor the means for producing them are shown). A typical output energy format is that of Figure 2*A* (where there is shown a graphical plot of output frequency against time). It has a saw-tooth ramp format (21), in which the frequency rises steadily over a period from one value to another, then drops almost instantaneously to the initial value — and repeats this rise and fall indefinitely.

In the absence of any physical perturbation of the fibre 16, light launched into the fibre in one particular linear polarization orientation (mode) remains wholely in that mode until it reaches the far end. Because, mathematically, it necessarily has a component at 45° to its orientation, that component is passed by the 45° analyser 18, and shines upon the detector 19. However, if the fibre is perturbed — say, by pressure at point *P* sufficient to cause physical deformation — then at *P* some of the lightwave energy in the original polarization orientation (mode) will be transferred into a linear orientation (mode) at right angles to this original one. Like the remaining energy in the original mode, this right angles mode energy will also travel on down the fibre, quite separately from, and independently of, the original mode energy, and will in due course reach the far end. But, because it necesarily travels at a speed different from that of the original mode energy, it will arrive at the far end slightly sooner — or later, as the case may be — than the original mode energy. The rightangles mode energy is also at 45° to the analyser. It too has a component at 45° to the analyser's orientation, and the analyser passes this component.

The two outputs of the analyser are shown in Figure 2*B* as graphical plots of the frequency of each output with time. The "main" output is a signal corresponding to the original saw-tooth of Figure 2*A* that was input to the fibre in the "original" orientation. The second output (22; shown dotted in Figure 2*B*) is spaced from the first (either output can be delayed relative to the other, though here it is implied that the second output 22 is a delayed version of the main output 21) by a time related to both the difference in speed of the two modes and the distance to the perturbation point *P*.

The analyser is thus passing the two 45° components — one from the original energy mode and one from the rightangles mode. Being of the same orientation these naturally interfere, and, having regard to their difference in frequency, do so in such a way as to produce beats in the combined energy, the frequency of these beats being determined by the delay of one mode relative to the other, and thus by the distance from *P* to the detector end of the fibre. The frequency of the beats is then used — by means not shown in the Figure — to compute the distance to point *P*.

In figure 1*B* there is shown a system similar to that of Figure 1*A* but using two transversal modes rather than two polarization modes. FMCW lightwave energy is launched into the fibre (116), which in this case is carefully dimensioned to support two transversal modes, *via* a mode filter (114; here a tight loop of fibre) which removes the higher order modes, leaving only a single mode (the fundamental mode) propagating down the fibre. At the receiving end of the fibre there is a detector 19 into which the light energy exiting from the fibre is

shone *via* the edge of an opaque mode mixer (118). In the event of some physical perturbation of the fibre occuring — say, at point *P* — then some of the energy in the fundamentral mode will transfer across into the second-order mode. This latter mode energy will then travel on down the fibre quite separately from, and independently of, the original mode energy. Both modes then exit the fibre end, and are mixed as they pass the opaque mixer 118 half blocking their path. Once mixed, they can interfere — and the interference results in beats that are detected and output (at 20) by the detector 19.

The embodiment shown in Figure 1*C* is a slightly more realistic version of the two-transversal mode variant of Figure 1*B*. Light energy from the generator is launched into the length of ordinary single mode fibre (116*g*) spliced (at the X) to the required two-transversal mode fibre 116, and light exiting the latter does so *via* another length of single mode fibre (116*d* spliced (the second X) on at the detector end. This second splice is deliberately a bad splice, and so serves as a mode mixer, like the opaque mixer 118 in Figure 1*B*..

Figure 3 shows a yet more realistic embodiment generally similar to the two-transversal mode systems of Figures 1*B* and 1*C*. A laser diode (31) the output of which is saw-toothed ramped (under the control of ramp device 32) and also temperature controlled (by temperature stabilizing device 33) has pigtailed thereonto a length of single mode fibre 116*g* spliced onto a long length of two-transversal mode fibre 116. To ensure that as launched the light energy in the main fibre 116 is only in the fundamental mode, a loop mode filter 114 is also employed.

The main fibre 116 has two portions. One (116*x*) is the actual sensor element, that part lying "exposed" between the two dashed lines. The other (116*s*), which is of roughly the same length as the exposed portion 116*x*, is coiled up out of harm's — and perturbation's — way. The exposed portion 116*x* is open to perturbation anywhere along its length, but certain shorter lengths, defined by the dotted boxes (34), have some particular significance (each may represent a defined area through which the fibre passes, or it may represent the location of a device that positively perturbs the fibre): At the far end of its second portion 116*s* the fibre is spliced (by a bad splice, so as to mix any single- and second-order-transversal mode energies) to another length of one-transversal mode fibre 116*d*, from which it exits to be focused by a lens 17 upon a detector 19. The detector's output is passed to a beat frequency detector (35), and the output of that is sent to the distance computing means (36).

It will be understood that the ability of the inventive system to allow multiple sensory inputs on the same length of fibre is based upon the outputs being beats at a different frequency depending upon the distance back to the perturbation points. Moreover, because of this — and provided only a relatively small amount of energy is transferred across at each perturbaton so as to reduce the problems of cross-coupling downstream thereof — many, if not all, of these can be active at one and the same time and yet give distinguishable outputs.

CLAIMS

1. A distributed-sensor system comprising:

a) an elongate sensor element, in the form of an optical fibre capable of supporting two modes of lightwave energy travelling along the fibre from one end to the other and, upon undergoing some localised physical perturbation, of allowing some of the energy in one mode to transfer at the perturbation locality to the other mode;

b) variable frequency continuous wave lightwave generation means, for generating lightwave energy to be launched into the fibre at one end thereof, the frequency of the lightwave varying with time;

c) single mode lightwave launch means at one end of the fibre, for launching the generated energy into the fibre in one of the two modes the fibre can support;

d) perturbation-inducing means at a locality somewhere along the fibre, for inducing a physical perturbation, or dimensional change, in the fibre, and thus for causing some lightwave energy to transfer across at that locality to the other of the two modes the fibre can support;

e) mode mixing and receiving means at the other end of the fibre, for mixing whatever lightwave energy arrives in the two modes at that end of the fibre, and for providing an output related thereto that varies in some manner dependent on the difference in frequency of the two lightwaves; and

f) position computing means operatively linked to the double mode lightwave receiving means, for calculating from the latter's output the position along the fibre of the induced perturbation.

2. A system as claimed in Claim 1, wherein the optical fibre has two two-mode portions, one of which operates as the sensor element capable of responding to perturbing forces and is coupled to the receiving means by the other (a similar length of two-mode fibre).

3. A system as claimed in either of the preceding Claims, wherein the sensor element optical fibre is capable of supporting lightwave energy either in the two modes represented by two orthogonal linear polarized lightwaves (and thus the fibre is birefringent) or in the modes supported by a two-transversal mode guide.

4. A system as claimed in any of the preceding Claims, wherein the lightwave energy is at a wavelength of about 830 nanometers.

5. A system as claimed in any of the preceding Claims, wherein it is arranged that any single perturbation causes of the order of 10% or less of the lightwave energy to be transferred from one mode to the other.

6. A system as claimed in any of the preceding Claims, wherein the means for generating the continuous wave lightwave energy is a single mode laser diode whose output is of a frequency/wavelength that is dependent on the driving current.

7. A system as claimed in any of the preceding Claims, wherein the lightwave energy generation

means' output's frequency/wavelength is saw-tooth ramped at a "constant" rate over some useful range appropriate to the generation and receiving means.

8. A system as claimed in Claim 7, wherein the rate at which the frequency/wavelength of the generating means output is varied is such as to provide a range scan (ramp) time of about 1 millisecond.

9. A system as claimed in any of the preceding Claims, wherein to employ orthogonally polarised light the launch means is a suitably orientated linear polarizer, or to employ two-transversal mode light the launch means is a mode filter to remove the unwanted mode.

10. A sensor system as claimed in any of the preceding Claims, wherein there is one or more actual perturbation-inducing means device that, triggered by some feature of the ambient conditions, physically perturbs the fibre at a chosen location.

11. A system as claimed in any of the preceding Claims, wherein there are several perturbation mens of different kinds.

12. A system as claimed in any of the preceding Claims, wherein the mode mixing and receiving means incorporates a photodiode detector component suitable to the lightwave energy involved.

13. A system as claimed in any of the preceding Claims, wherein to combine at the mode mixing and receiving means the lightwave energies arriving in each mode there is, when the two modes are orthogonal linear polarization modes supported in a birefringent fibre, an "analyser" set at 45° to each that will pass a proportion of both in the common plane, and where the two modes are transversal modes, a partial block at the "out" end of the fibre.

14. A system as claimed in Claim 13, wherein where the sensor element fibre is spliced to another length of fibre, this splice — provide it is a fairly *bad* splice — will itself act as the partial block causing two transversal modes to combine.

15. A system as claimed in any of the preceding Claims, wherein the means for accepting the output of the receiving means, and computing therefrom the position along the fibre of the perturbation locality, is a device for outputting a signal — the distance information — the magnitude of which is directly proportional to the beat frequency of the receiving means output.

16. A distributed-sensor system as claimed in any of the preceding Claims and and substantially as described hereinbefore.

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